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SECONDARY ELECTRON EMISSION FROM SODIUM  
CHLORIDE, GLASS AND ALUMINUM OXIDE AT  
VARIOUS TEMPERATURES

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At present many questions which are essential to the understanding of the emission of secondary electrons from dielectrics remain incompletely answered. Among these questions are: the depth of penetration of primary electrons, the production mechanism of secondary electrons, the energy range of solids which are sources of secondary electrons, the depth of emission of secondary electrons, and the energy-loss mechanism of electrons.

In order to investigate some of these questions, we undertook a series of experiments. In one of these experiments we studied secondary electron emission at various temperatures. The results are presented in this article.

A study of the temperature dependence of the secondary electron emission coefficient,  $\sigma$ , could shed light on the energy-loss mechanism of secondary electrons. Unfortunately, the data in the literature are very sparse, and they cannot be used as a basis for definite conclusions.

By now it can be considered as established that the coefficient of secondary electron emission for metals is independent of temperature. There are several reports that show that  $\sigma$  for dielectrics is also independent of temperature. This was noted by Vudinskiy [1], who studied thin films of NaCl; Mueller [2] and Blankenfeld [3] with glass; and Sul'man and Rozenweig [4] with aluminum oxide. Moreover, a decrease in  $\sigma$  with increasing temperature was observed [Ref. 3] with magnesium oxide. This was noted by Salow [5] as well. Apparently the temperature dependence of  $\sigma$  in the case of semiconductors is much more complicated. This was first investigated by Morgulis and Nagorskiy [6].

Hachenberg [7], in studying the problem of surface absorption,

\*Numbers in margins indicate foreign pagination.

tion of secondary electrons, concluded that in the case of dielectrics with a small number of lattice defects, there are only phonon losses. As a result,  $\sigma$  should be proportional to  $1/T$ . In the case of dielectrics with a large number of lattice defects, the interaction of secondary electrons with the lattice defects plays a fundamental role, and  $\sigma$  should not depend on temperature for these dielectrics.

To ensure that experiments to study secondary emission from dielectrics yield convincing and reliable results, it is necessary to take several precautions to avoid spurious effects, which arise from the bombardment of dielectrics with electrons (change in the work function of the dielectric, change in the emitter material). Another requirement is that one be able to measure  $\sigma$  at any temperature.

#### METHOD OF MEASUREMENT

In order to avoid the difficulties mentioned above, a method/1153 of single pulses was developed and used in our laboratory [8].

The tube used was an envelope with two ground-glass joints. The electron gun was of standard construction with a tungsten cathode. The gun had a special diaphragm to which was applied a negative voltage on the order of 100 volts relative to the grounded anode. This was necessary to protect the collector and target from slow electrons, which are produced by fast electrons striking the edge of the anode diaphragm, and to steer the secondary electrons to the collector.

A constant, regulating voltage in the range 0-450 volts was applied to the steering electrode of the gun. This completely blocked the gun. It was started by a pulse generator in the

steering electrode circuit. The magnitude of the starting pulse was selected such that, when added to the constant bias potential, the resultant corresponded to the maximum of the response curve of the steering electrode. This produced well-shaped primary current pulses. The accelerating potential was stabilized to a precision of 0.5%, which was essential to the stability of the single pulses.

The diameter of the beam was approximately 2-3 mm. The apparatus allowed the beam to be locked onto the target.

The target backing (signal plate) was a metal ribbon, 30-50 microns thick and 3-3.5 mm wide. The dielectric target was fastened to this support. The target was heated by passing an electric current through the backing.

The tube, amplifier, heater and associated wiring were carefully screened. The absence of induction, in particular by applying the pulses to the steering electrode, ensured the screening action of the anode (which was connected to the neutral wire of the circuit) and the blocking of the third diaphragm by a large capacitor.

With this apparatus, secondary electron emission could be measured by three methods: a) the normal method using a constant electron beam; b) 30-100 microsecond-wire periodic pulses; c) single pulses of the same duration.

In the case of constant current, a galvanometer was used to make the measurement. With the galvanometer in the target circuit, and thus dependent on the polarity of the collector voltage, either the primary current or the difference between the primary and secondary current could be measured. With the galvanometer in the

collector circuit and a negative potential (whose magnitude was subtracted from  $V_p$ , the accelerating potential of the primary beam) applied to the target, the secondary current was measured. In this case the primary current was measured as the sum of the target and collector currents.

In the case of periodic pulses, the galvanometer was replaced by a set of resistors in the range 1.25-20 kilo-ohms. The voltage pulses were taken from these resistors and applied to the grid of the first tube of the amplifier. Then, amplified, they were immediately applied to the plates of an oscilloscope.

The primary current pulses were measured by inserting a resistor in the common collector-target circuit. In this case there was a negative potential of 70 volts on the signal plate. This method of measurement has several advantages over the others. /1154 In measuring the secondary current, the parasitic capacitance is added to the collector and mounting capacitances, whereas in measuring the current difference,  $i_1 - i_2$ , the target circuit, the parasitic capacitance of the target heater is added. Moreover, with this method of measurement the primary and secondary current pulses have the same polarity (negative with respect to the neutral wire of the circuit), simplifying the amplifier design.

In measuring the primary current with the target heater circuit closed, the accumulation time is increased due to the increase in parasitic capacitance. This limits the accuracy of measurements (errors on the order of 5-10%).

In the case of single pulses, the measurements were made in the same manner as with periodic pulses except that special measures were taken to stabilize the pulses. The single pulse was produced by the same pulse generator, which in this case was

triggered not by the multi-vibrator but by the voltage peak produced by discharging a special capacitor.

The pulse generator consisted of a) a trigger stage with two 6N7 tubes; b) a delay stage (6S5, 6N7, 6F6); c) a stage which produced square pulses (6F6, 6P3); and d) an amplifier 6AG7.

The amplifier was of standard design with a gain of approximately 120,000. The upper limit of the pass-band was about 600 kHz. The amplitude was linear up to an output voltage of 70 volts.

With the method of single pulses, surface discharge in the target after the pulse (in the case of a low conductivity target) caused heating of the target and subsequent cooling. We did not use the method of discharge by irradiation of the surface with slow electrons since this method can introduce errors caused by the formation of a double layer and a change in the target material.

#### CONTROL EXPERIMENT

In order to verify the experimental method, the dependence  $\sigma = f(V)$  was measured for a molybdenum target at room temperature and in the temperature range 900-1100°C. The curve obtained using the three methods of measurement outlined above for measuring  $\sigma$  were identical and agreed very well with the data of Warnecke [9]. The temperature was measured with an optical pyrometer.

#### SECONDARY EMISSION FROM ALUMINUM OXIDE FOR SEVERAL TEMPERATURES AND TARGET BACKINGS

In the work reported here aluminum oxide of two types was used. In what follows, they will be referred to as type 1 and 2.

The experiments showed that there is a significant difference in secondary emission from the two types of aluminum oxide. Moreover, preliminary experiments had already shown that after treating the aluminum oxide at high temperature, secondary emission from the alundum target also depended on the material of the target backing. Therefore  $\sigma$  for aluminum oxide was measured for different backings: molybdenum, tantalum, and platinum.

The signal plate (backing) was annealed first in a forevacuum at various temperatures (platinum at  $1500^{\circ}\text{C}$ , molybdenum and tantalum between  $1800$  and  $1900^{\circ}\text{C}$ ). Then a brush was used to deposit a uniform layer of alundum suspended in alcohol. After /1155/ drying, the target was annealed in vacuum at various temperatures (depending on the backing material) and then aged. The aging of the target consisted of annealing it at high temperature for various periods of time with either an electron or ion thermo-emission current. As a result the alundum was purified of several contaminants (electropurification).

a) Measurements of Aluminum Oxide with a Platinum Backing

Single pulses of duration 30-100 microseconds were used in the measurements. The backing was a platinum foil of 50 micron thickness. Aluminum oxide of type 1 was investigated.

The results of the measurements of the dependence of  $\sigma$  on the energy of the primary electrons at room temperature are shown in Figure 1. Curve 1 was obtained at a vacuum better than  $2 \times 10^{-6}$  Torr after the target had been annealed in a fore-vacuum. Curve 2 shows the results after the target was heated to  $1400^{\circ}\text{C}$  in a vacuum. Hence, with a single target the magnitude and behavior of  $\sigma$  depends on the prior target preparation. This preparation may result in purification of the aluminum oxide of various impur-

ties and in outgassing the target. The experiments indicated that if the target were outgassed sufficiently well, differences in aging the target had little effect on the magnitude and behavior of  $\sigma$ . On the other hand, insufficiently outgassing of the target resulted in a significant change in the size and behavior of  $\sigma$ .

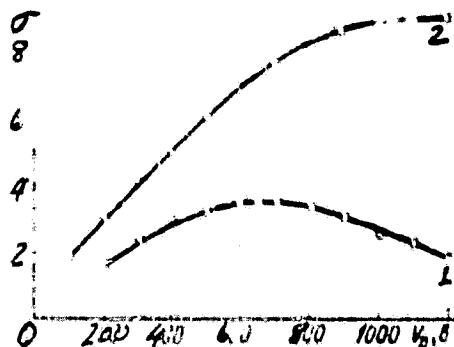


Figure 1. Dependence of  $\sigma$  on primary electron energy.  $\text{Al}_2\text{O}_3$  on Pt.

1 - prior to heating in a vacuum  
2 - after heating in a vacuum

After curve 1 of Fig. 1 was obtained, the target was heated to gradually higher temperatures. This caused  $\sigma$  to increase until the temperature reached approximately  $1400^\circ\text{C}$ , after which  $\sigma$  remained constant, at which point the curve shown in Fig. 2 was obtained. Further increase or decrease in the temperature did not change the curve.

Curve 1 could be reproduced by keeping the target in a forevacuum for a period of time. It is interesting to note that any curve between 1 and 2 could be obtained depending on how long the target was in the forevacuum.

If after obtaining curve 2 the target was kept for a long time (4 hours) in a high vacuum, subsequent measurements completely reproduced curve 2.

These facts indicate that curves of type 1 are not characteristic of secondary emission from aluminum oxide but rather are a result of electron bombardment of a dielectric having a surface film which can only be removed by careful heating of the target. Therefore, the data for which the aluminum oxide was prepared in air and then introduced into the apparatus without careful out-gassing and heating, cannot be directly ascribed to aluminum oxide. /1156

Consequently we consider curve 2 of Fig. 1 to be characteristic of the secondary emission property of aluminum oxide on a platinum backing.

The temperature dependence of  $\sigma$  for aluminum oxide on a platinum backing is shown in Fig. 2. As is obvious,  $\sigma$  is independent of temperature in the range 0-1500°C. Curves obtained at the other values of  $V_p$  that we used are similar to the curve of Fig. 2.

Measurements were made for five targets. All gave similar results. For  $V_p = 600$  volts,  $\sigma$  varied between 6.9 and 7.1 for the different targets.

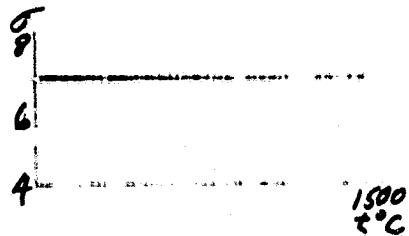


Figure 2. Temperature dependence of  $\sigma$ .  
 $\text{Al}_2\text{O}_3$  on Pt.  $V_p = 600$  volts.

b) Measurements of Aluminum Oxide with a Molybdenum Target

Measurements of the same sort for aluminum oxide on a molybdenum backing gave different results. First of all the value of

$\sigma_{\max}$  increases. For aluminum oxide on a platinum backing  $\sigma_{\max}$  is equal to 9 for  $V_p = 1100$  volts, whereas with a backing of molybdenum it is equal to 11.5 for  $V_p = 800$  volts. The value of  $V_p$  for which reaches a maximum decreases.

A more significant difference is that  $\sigma$  has an obvious temperature dependence (Fig. 3). The change in  $\sigma$  occurs in a restricted temperature interval, below which  $\sigma$  is temperature independent. This result was consistently reproduced in repeated measurements. A total of six targets was measured, all giving similar results.

As in the previous case, the absolute value of  $\sigma$  and the dependence  $\sigma = f(V_p)$  depend on the degree of outgassing of the target.  $\sigma = f(V_p)$  is shown in Fig. 4 for poorly and well-outgassed targets. If the target is heated in a vacuum at  $1500^{\circ}\text{C}$  before measurement, curve 2 is obtained. This curve is reproduced very well after leaving the target in a high vacuum for several hours. It is interesting to note that different methods of aging the target have little effect on the value and behavior of  $\sigma$ .



Figure 3. Temperature dependence of  $\sigma$ .  $\text{Al}_2\text{O}_3$  on Pt.  $V_p = 600$  volts.

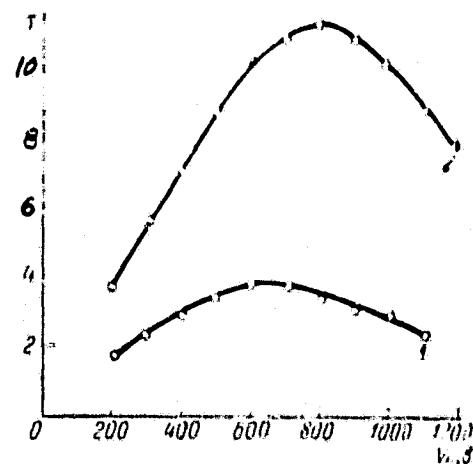


Figure 4. Dependence of  $\sigma$  on primary electron energy.  $\text{Al}_2\text{O}_3$  on Mo.  $T = 300^{\circ}\text{K}$   
 1 - before heating in vacuum  
 2. after heating in vacuum

c) Measurements of Aluminum Oxide (type 1) on a Tantalum Backing

This case is intermediate with respect to the two cases discussed above. A total of five targets of alundum of type 1 was measured. Three of them exhibited a behavior similar to that with a platinum backing. The corresponding curves are shown in Fig. 5 and 6. For two of the targets  $\sigma$  showed a weak temperature dependence. For one of these (Fig. 7) the effect was reproducible, but for the other it was not.

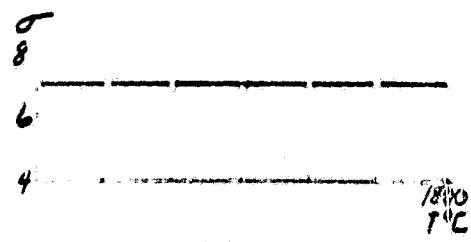


Figure 5. Temperature dependence of  $\sigma$ .  $\text{Al}_2\text{O}_3$  on Ta.  $V = 600$  volts. Type 1.

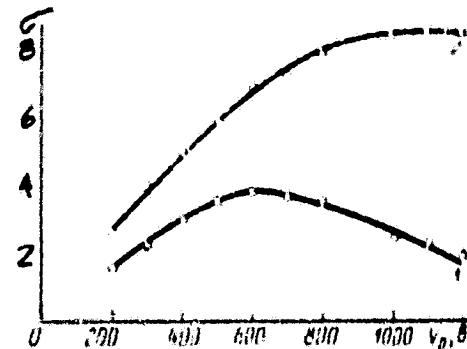


Figure 6. Dependence of  $\sigma$  on primary electron energy.  $\text{Al}_2\text{O}_3$  on Ta.  $T = 300^\circ\text{K}$ .  
 1 - before heating in vacuum.  
 2 - after heating in vacuum.

d) Measurements of Aluminum Oxide (type 2) on a Tantalum Backing

In this case with the target prepared in the normal fashion, the results differed from the previous ones. First we found that the value of  $\sigma$  was lower than for type 1. The variation of  $\sigma$  with  $V_p$  was also different (Fig. 8). For  $V_p$  approximately equal to 500 volts,  $\sigma$  reaches a maximum. There was no dependence on temperature up to  $1500^\circ\text{C}$ .

These data agree with the measurements of secondary emission  
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from aluminum oxide of this type which were made previously in our laboratory [1].

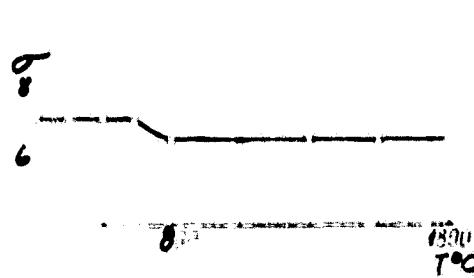


Figure 7. Temperature dependence of  $\sigma$ .  $\text{Al}_2\text{O}_3$  on Ta.  $V_p = 600$  volts. Type 1.

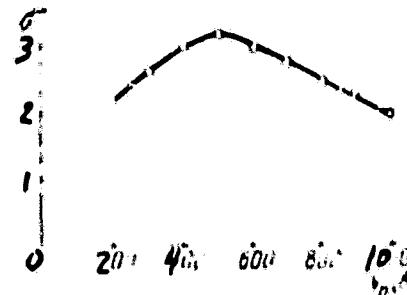


Figure 8. Dependence of  $\sigma$  on primary electron energy.  $\text{Al}_2\text{O}_3$  on Ta.  $T = 300^\circ\text{K}$

#### SECONDARY EMISSION FROM MONOCRYSTALLINE NaCl AT VARIOUS TEMPERATURES

/1158

Research on secondary electron emission from alkyl halide compounds has up to the present been carried out on films deposited on the target in a vacuum. The method we used allowed us to measure the emission from the material for various temperatures and conditions. We measured the secondary emission from monocrystalline sodium chloride.

A natural crystal of NaCl was polished with silk, moistened with water, reduced to a thickness of 0.5 mm, and then placed in the apparatus. A total of five targets was measured. The dependence of  $\sigma$  on  $V_p$  is shown in Fig. 9 (curve 1). The values of  $\sigma$  are small, and the maximum occurs at a relatively low value of  $V_p$ .

After heating the target in vacuum at  $500^\circ\text{C}$ , the curve changed radically (see curve 2). A similar phenomenon was observed with aluminum oxide. In the temperature range up to  $500-600^\circ\text{C}$   $\sigma$  is independent of temperature (Fig. 10).

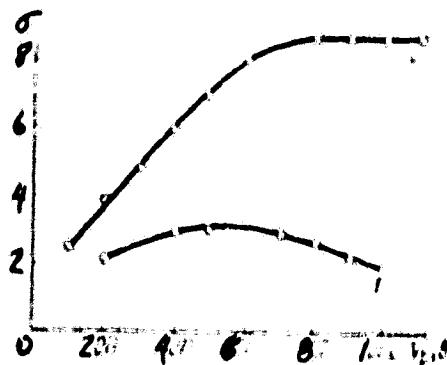


Figure 9. Dependence of  $\sigma$  on primary electron energy.  
Monocrystalline NaCl.  
 $T = 300^{\circ}\text{K}$ .

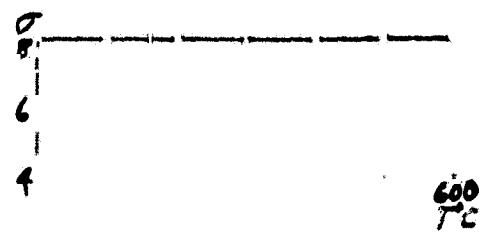


Figure 10. Temperature dependence of  $\sigma$ . Monocrystalline NaCl.  
 $V_p = 600$  volts.

For temperatures greater than  $500-600^{\circ}\text{C}$  we observed a rapid increase in  $\sigma$  to 12 or 13. Simultaneously there was marked decrease in the size of the primary current pulse. These results can be explained in the following manner: at high temperatures the NaCl molecule dissociates. The formation of Na ions evidently causes the increase in emission. The Cl ions hitting the cathode of the gun poison it, causing a decrease in pulse size. Hence we can conclude that until the structure of NaCl changes,  $\sigma$  is independent of temperature. The temperature dependence is a result of a change in the target material.

#### SECONDARY EMISSION FROM GLASS No. 46 AT VARIOUS TEMPERATURES

The thickness of the glass used was 0.5 mm. It was fastened to a nickel backing. Measurements were made on four targets.

Results of the measurements are shown in Fig. 11 and 12.  $\sigma$  is independent of temperature and has a relatively sharp maximum at

$V_p = 450$  volts. The magnitude of  $\sigma$  is not large.

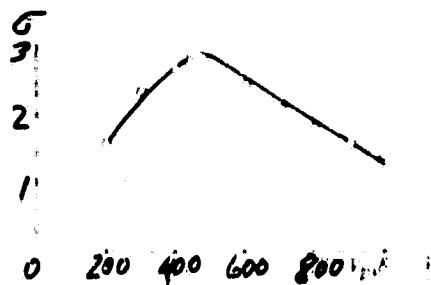


Figure 11. Dependence of  $\sigma$  on primary electron energy. Glass No. 46.  $T = 300^{\circ}\text{K}$ .

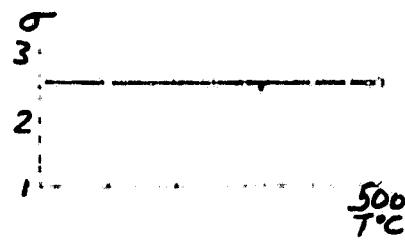


Figure 12. Temperature dependence of  $\sigma$ . Glass No. 46.  $V_p = 600$  volts.

In this case the effect of heating the target is significantly less than the previous cases. The value of  $\sigma$  (at  $V_p = 600$  volts) increases from 2.1 - 2.2 to 2.4-2.5 as a result of heating. After placing the target in a forevacuum,  $\sigma$  returns to its previous value of 2.1 - 2.2 ( $V_p = 600$  volts).

This behavior can be explained by assuming that heating the target to a temperature of  $450-500^{\circ}\text{C}$  is not enough to remove the gas film or that the emission property of glass No. 46 differ little from that of glass coated with a gas film.

#### DISCUSSION OF RESULTS

$\sigma$  was observed to be independent of temperature for three typical dielectrics (glass, NaCl, and aluminum oxide) with a platinum backing over a wide temperature range. This result can be interpreted in the following way. It appears that for the materials cited above the energy lost by secondary electrons in Coulomb interactions with electrons in the conduction band is small. This is because the number of electrons in the conduction band, even at high temperatures, is not large enough to have a noticeable ef-

fect on  $\sigma$ . In addition, phonon losses are evidently insignificant. The absence of energy loss can possibly be explained by the fact that in our experiments the depth of production of secondary electrons is not great. This, however, must be shown by direct experiments, which in particular examine the temperature dependence of  $\sigma$  at large  $V_p$ .

Hachenberg [7] has shown that for NaCl and aluminum oxide of type 1, one would expect  $\sigma$  to be inversely proportional to  $T$ . This, however, was not observed in the experiments. The absence of temperature dependence in  $\sigma$  in the case of glass is as predicted by Hachenberg.

It is interesting to compare the data on the temperature dependence of  $\sigma$  with the form of the curves  $\sigma = f(V_p)$ . These curves for aluminum oxide of type 1 and NaCl have a flat maximum at relatively large values of  $V_p$ . Such behavior has been observed in several dielectrics by other authors. The curves for glass and aluminum oxide of type 2 have a relatively sharp maximum at lower values of  $V_p$ .

If these curves are interpreted in the usual manner (see, for example, Ref. 10), one would expect no temperature dependence of  $\sigma$  for aluminum oxide of type 1 and NaCl in the region of  $V_p$  used, whereas for aluminum oxide of type 2 and glass, losses should be significant. However, according to Hachenberg losses due to defects should play a significant role in glass, and this should be expressed as an absence of temperature dependence. The noted /1160 agreement ought not to serve as a basis for immediate conclusions since it is possible that the curve  $\sigma = f(V_p)$  reflects not only loss mechanisms but also differences in the production of secondary electrons with increasing energy.

The data obtained by us on a secondary emission from aluminum oxide of type 1 on a molybdenum backing stand somewhat apart. These data indicate that  $\sigma$  is temperature dependent. A student in our laboratory, V. E. Chelnokoviy, showed by direct experiment that under certain conditions of thermal preparation of aluminum oxide on a molybdenum backing, some particles of molybdenum penetrate into the target material. This means that aluminum oxide on molybdenum is a more effective emitter than aluminum oxide whose composition remains unchanged. Therefore we conclude that the observed change in  $\sigma$  with temperature is related to a change in the target material and not to a change in the secondary emission of pure aluminum oxide.

The values of  $\sigma$  for the aluminum oxide of type 1 and NaCl that we measured are relatively high. It should be noted that such high values are obtained only with targets that have been well outgassed. In the case of insufficient outgassing, e.g. with aluminum oxide on platinum, the value of  $\sigma_{\max}$  falls from 7.1 to 3. The value of  $\sigma$  for glass agrees well with the data of Ref. 2 and 3 as well as others.

It should be noted that outgassing not only affects the value of  $\sigma$  but also the shape of the  $\sigma = f(V_p)$  curve. For insufficiently outgassed targets the maximum value of  $\sigma$  occurs at lower values of  $V_p$  than for well outgassed targets.

#### CONCLUSIONS

1. The single pulse method was used to measure secondary electron emission from dielectrics.
2. The coefficients of secondary electron emission from aluminum oxide of two types, monocrystalline sodium chloride and glass were measured at various temperatures and energies of the pri-

many electrons.

3. The existence of a gas film on the surface of the dielectric affects the value and behavior of  $\sigma$ .
4. For sodium chloride, aluminum oxide, and glass  $\sigma$  is temperature independent.
5. The backing material influences the value and behavior of  $\sigma$  when the target is subjected to preparation at high temperatures.
6. A possible interpretation of the observed facts is given.

This work was completed in the laboratory of academician P. I. Lukirskiy, to whom the authors wish to express their appreciation for the assistance rendered.

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